ONSET AND SUPPRESSION OF PLASMA INSTABILITY

IN CROSSED-FIELD GEOMETRY

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INTRODUCTION

A large number of previous experiments performed in linear Hall accelerators (refs. 1-5) has revealed the existence of low frequency (1-100 kHz), azimuthally rotating, nonuniformities, which are associated with instabilities in the plasma. Some of these experiments have shown the dependence of the frequency of rotation on magnetic field, pressure, and arc current. However, no onset of the instability at a critical magnetic field has been reported in the literature for this geometry.

In most of the earlier experiments considerable attention was given to the magnetic field uniformity in the anode region of the device and over a major part of the interelectrode distance. The cathode, however, was located outside the uniform field region. The instability was thought to originate in the anode region. In reference 5 the effect which the radial and axial components of magnetic field in the anode region had on the instability was investigated. It was then thought that the axial component of magnetic field near the anode controlled the instability. The possibility of such an effect was supported by the independent theoretical work of reference 6. However, the requirement of independent radial and axial magnetic-field components in the anode region produced in the cathode region a highly nonuniform field which could not be controlled. In an effort to understand the effect which the magnetic field near the cathode had on the instability, the present geometry was set up, with uniformity of the radial magnetic field extending over the entire anode to cathode region. The axial magnetic field is negligibly small. In addition, because of the uniformity of the applied magnetic field in the cathode region, it was possible to evaluate the effect on the instability of the magnetic field produced by the dc heating current of the wire cathode. Such wire cathodes, usually tungsten heated to thermionic emission temperature, were used in the majority of the referenced experiments. The dc heating current produces an approximately $1/r$ magnetic field which, in the region close to the cathode, can be of the order of the applied magnetic field. In at least one experiment (ref. 2) the cathode was wound so as to minimize the perturbation, but the present results indicate that minimization may not be sufficient since very small values of magnetic field are found to cause instability, particularly at low pressure of the order of 1 m Torr. which was the pressure used in reference 2 as well as in the present experiment.

In the present geometry, an onset of the instability for a critical value of radial magnetic field has been observed. The cathode region is shown to be the area of origin of the instability, and the instability can be suppressed throughout the region between the electrodes by controlling the radial magnetic field near the cathode only. It was also found that introduction of an axial component of magnetic field, of the same order as that of the radial component required for onset, had no effect on the onset of the instability.

APPARATUS

A schematic of the linear Hall accelerator is shown in figure 1. The anode is a water-cooled copper ring 5.5 cm i.d. and 7.5 cm o.d. The cathode is a 1 mm diameter tungsten wire which is shaped into an almost-closed circle of 7 cm diameter, which is in the center of an annulus of 5 cm i.d. and 9 cm o.d. The cathode-to-anode distance is 12.5 cm. The working gas is injected at the anode so that the flow is from anode to cathode. The cathode is heated with either a dc current of 70 amperes or with a 60 Hz ac half-wave rectified current with a peak current of 70 amperes.

A nearly uniform radial magnetic field extending from cathode to anode is produced by a central iron core and an external coil placed about 20 cm from the cathode. The maximum value of the radial magnetic field was about 180 gauss. This externally applied field fell off approximately as 1/r away from the iron core, and the values given are those at the mid-point of the annulus. The iron core was covered by a boron-nitride insulator.

Stationary probes constructed of tungsten wire 0.2 mm diameter and 1.5 mm long were inserted at various axial and azimuthal positions through a glass tube containing the discharge. If we let the anode be at $z = 0$, one set of probes was located at $z = 2.5$, 5, 7.5, and 10 cm. A second set of probes was located at the same axial positions, but displaced 90° from the first set. All probes are displaced by approximately 1/2 cm inward from the outside glass wall.

Probe signals were fed into a Panoramic Spectrum Analyzer or a Tektronix type 555 dual-beam oscilloscope. Measurements were made of the floating potential and the ion saturation current. The measurements were made in argon, xenon, helium, and nitrogen at pressures ranging from one to 200 m Torr. The majority of data were taken with an arc current of 2.5 amperes.

RESULTS AND DISCUSSION

Use of a dc cathode heating current of 70 amperes produces a magnetic field around the cathode wire which was calculated to be about 300 gauss at the surface of the wire, falling off to about 15 gauss 1 cm from the surface of the wire. With zero external magnetic field (defined as B_r) oscillations were observed at all probes. (Pressure is 10 m Torr in argon and arc current is 2.5 amperes unless otherwise noted.) Figure 2(a) shows the frequency spectrum of this oscillation at a probe located 2.5 cm from the cathode. The phase shift between two probes at the same axial position (2.5 cm from the cathode) and displaced 90° azimuthally is shown in figure 2(b) and shows the perturbation to be rotating azimuthally with an $m = 1$ mode. (Cathode positive and cathode negative refer to the radial component of the magnetic field of the cathode wire on the upstream (anode) side of the cathode. This component is defined as B_{rc}. Positive means radially outward.)

Reversal of the cathode heating current with consequent reversal of the associated self-magnetic field produced the results shown in figures 2(c) and 2(d). The oscillation exhibits the same frequency, but the direction of rotation has reversed due to the reversal in the magnetic field of the cathode wire.

As mentioned above, the frequency spectra and phase-shift measurements shown in figure 2 were made using a probe located 2.5 cm from the cathode. A probe located 2.5 cm from the anode showed the presence of oscillations which had the same frequency as those at the cathode probe, but with $m = 0$. Similar measurements at higher B_r to be described later showed an $m = 1$ helical perturbation at all probes. This variation of mode at $B_r = 0$ and B_{rc} finite is still under investigation.

If now a 60 Hz ac half-wave rectified heating current is used, it is possible to examine the probe signals during that portion of the cycle when the heating current and its associated magnetic field are zero, but the cathode is still hot enough to emit thermionically. It is found that for zero external field, B_r, the plasma is quiescent, and without oscillations. As B_r is increased from zero an onset of coherent oscillations is observed at $B_r \gtrsim \pm 15$ gauss. The direction of rotation is in the drift or $\vec{E} \times \vec{B}$ direction.

Next, it will be shown that the existence of a quiet state depends only on the existence of a subcritical field near the cathode and not throughout the device. This is done by making use of the self-magnetic field of the dc cathode heating current. The current is applied such that B_{rc} is positive. The external radial field B_r is applied negatively so that it subtracts from B_{rc}. The resulting spectra and phase-shift measurements are shown in figure 3. Figure 3(a) shows the spectrum at $B_r = -10$ gauss, showing the frequency to have decreased slightly from the $B_r = 0$ condition. At $B_r = -20$ gauss, the perturbation disappears abruptly, the discharge becoming quiet throughout the interelectrode region, as shown in figure 3(b). (The signal at zero frequency is a zero marker internally generated by the analyzer.) The quiet state shown in figure 3(b) persists as B_r is varied further to about -40 gauss, at which value the coherent oscillation reappears, as shown in figure 3(c). Further variation of B_r increases the frequency of rotation. The phase-shift measurements of figures 3(d) and 3(e) show that the direction of rotation is opposite for these two conditions.

If B_r is applied positively such that it adds to B_{rc}, no quiet state is observed, the coherent oscillation observed at $B_r = 0$ increases in frequency as B_r increases.

The conclusion to be drawn from the observations is that the onset of the instability, its direction of rotation, and its frequency are controlled by the total magnetic field $B_r + B_{rc}$ in a critical region close to the cathode. The approximate location and width of this region can be deduced as follows: For the dc cathode measurements, with B_{rc} positive, the plasma is quiet in the range $-20 \gtrsim B_r \gtrsim -40$ gauss, with onset occurring for the two end values. Since the critical field required for onset is symmetrical about a zero magnetic field for the ac heated cathode measurements, it is assumed that the same is true for the dc heated cathode. The zero point is taken to be the center of the quiet range, $B_r = -30$ gauss. So for $B_r = -30$ gauss, we must have $B_r + B_{rc} = 0$ locating the center of the critical region at a distance of about 0.5 cm from the cathode. The width in gauss of the quiet state places an upper limit on the width of the critical region of 0.35 cm.

The influence which the confining walls have on the onset of the instability has also been examined. In the results described above, the cathode was placed inside the glass tube, about 4 cm from the end of the tube. The confining surfaces, glass tube on the outside and boron-nitride insulator on the inside, were each about 1 cm from the cathode wire. In an additional experiment, the cathode was placed about 4 cm downstream of the end of the glass tube so that the only confining surface was the inside boron-nitride insulator. For this configuration a double quiet state was observed, one for positive B_r and one for negative B_r (with B_{rc} held to one direction). The second quiet state was apparently due to cancellation of B_{rc} on the downstream side of the cathode. The fact that this second quiet state disappears when the cathode is confined by both the boron-nitride insulator and the outside glass tube indicates that the walls may act as a buffer to the electrons emitted on the downstream side of the cathode.

The pressure dependence of the critical field required for onset is shown in figure 4 for different gases. These results were obtained using the ac heated cathode. The curves are seen to be nonlinear at the lower pressures, but all are apparently linear at the higher pressures.

Figure 5 shows the frequency of rotation as a function of magnetic field for three pressures in argon. Similar curves were obtained earlier (ref. 7) and have two distinguishing characteristics: (a) lower frequency for higher pressures at a given B, and (b) the droop in the curves at higher B for the lower pressures.

The axial density distribution for this geometry has been shown by Chubb and Seikel (ref. 8) to have a peak at $\frac{z}{L} \simeq \frac{1}{3}$ (where L is the interelectrode distance, and $z = 0$ is the anode), the measurements being made with $B_r = 200$ gauss in the presence of large oscillations in the plasma potential. Preliminary ion density measurements in the present experiment in the presence of oscillations show a similar distribution, but with the appearance of a second density peak in the region close to the cathode (less than 1 cm from the cathode). The data of reference 8 indicate the possible existence of a similar peak near the cathode in that experiment.

The density distribution described above is found to exist only when oscillations are present, the onset being accompanied by a sharp change in the distribution. In particular, for the quiet state the density is found to increase constantly from anode to cathode up to a distance less than 1 cm from the cathode after which it decreases.

The increase in density near the cathode is important in that it allows a possible interpretation of the experimental results on the basis of the model for instabilities in crossed-field geometry proposed by Simon (ref. 9). A quantitative comparison of experimental values of critical field required for onset (fig. 4) with the theory is difficult in view of the difference between the experimental and theoretical geometries. However, the density measurements show that the necessary condition for onset derived by Simon, namely that $E_A \frac{dn}{dz} > 0$, is fulfilled in the critical region near the cathode. (E_A is the applied electric field and $\frac{dn}{dz}$ is the axial density gradient.) Further, the direction of rotation is always in the $\vec{E} \times \vec{B}$ direction as it should be according to Simon's model, where, for the present case, $B = B_r + B_{rc}$ in the critical region near the cathode.

SUPPLEMENTARY RESULTS ON ROTATING INSTABILITIES IN HIGH-POWER MPD ARC

A low-frequency rotating instability ($100 \leq f \leq 250$ kHz) exhibiting an abrupt onset at a critical magnetic field which depends upon arc current has also been detected in the exhaust jet and in the interelectrode region of a relatively high-power MPD arc thruster, using argon as the working gas, with a mass flow of 14 milligrams/sec. The power of the arc ranged from 10 to 25 kw.

These results were obtained from measurements of floating potential and ion density using Langmuir probes. Axial and azimuthal phase-shift measurements of the signals were made. Time-resolved light intensity measurements were also obtained by taking streak photographs of the light emitted in the interelectrode region of the arc. For currents of 300, 400, and 500 amperes, the critical magnetic field for onset B_c was approximately 800, 640, and 480 gauss, respectively. Above onset, the instability rotated in the $\vec{E} \times \vec{B}$ direction and exhibited two frequency peaks ($f_1 \simeq 100$ kHz and $f_2 \simeq 180$ kHz). Both frequency peaks increased almost linearly with increasing magnetic field, up to a magnetic field strength of 5500 gauss.

From these preliminary measurements, it is indicated that the rotating instability exists both in the exhaust jet and in the interelectrode region of the MPD arc, and that onset of the instability occurs throughout the device. In reference 10, the formation of a rotating current spoke for an MPD arc in the presence of a strong magnetic field (say about 500 gauss) has been recently mentioned by Malliaris.

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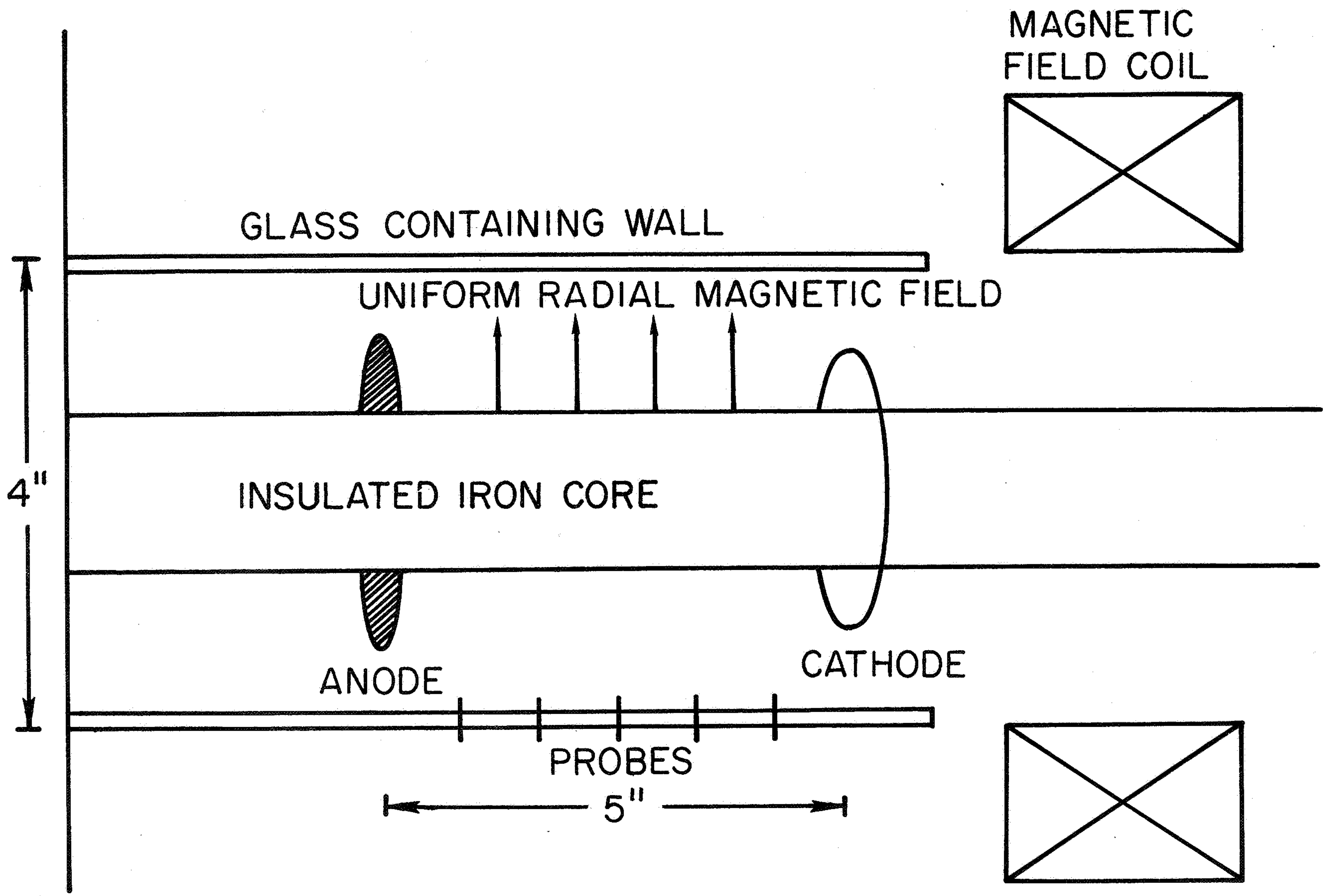

Figure 1.- Linear hall current accelerator.

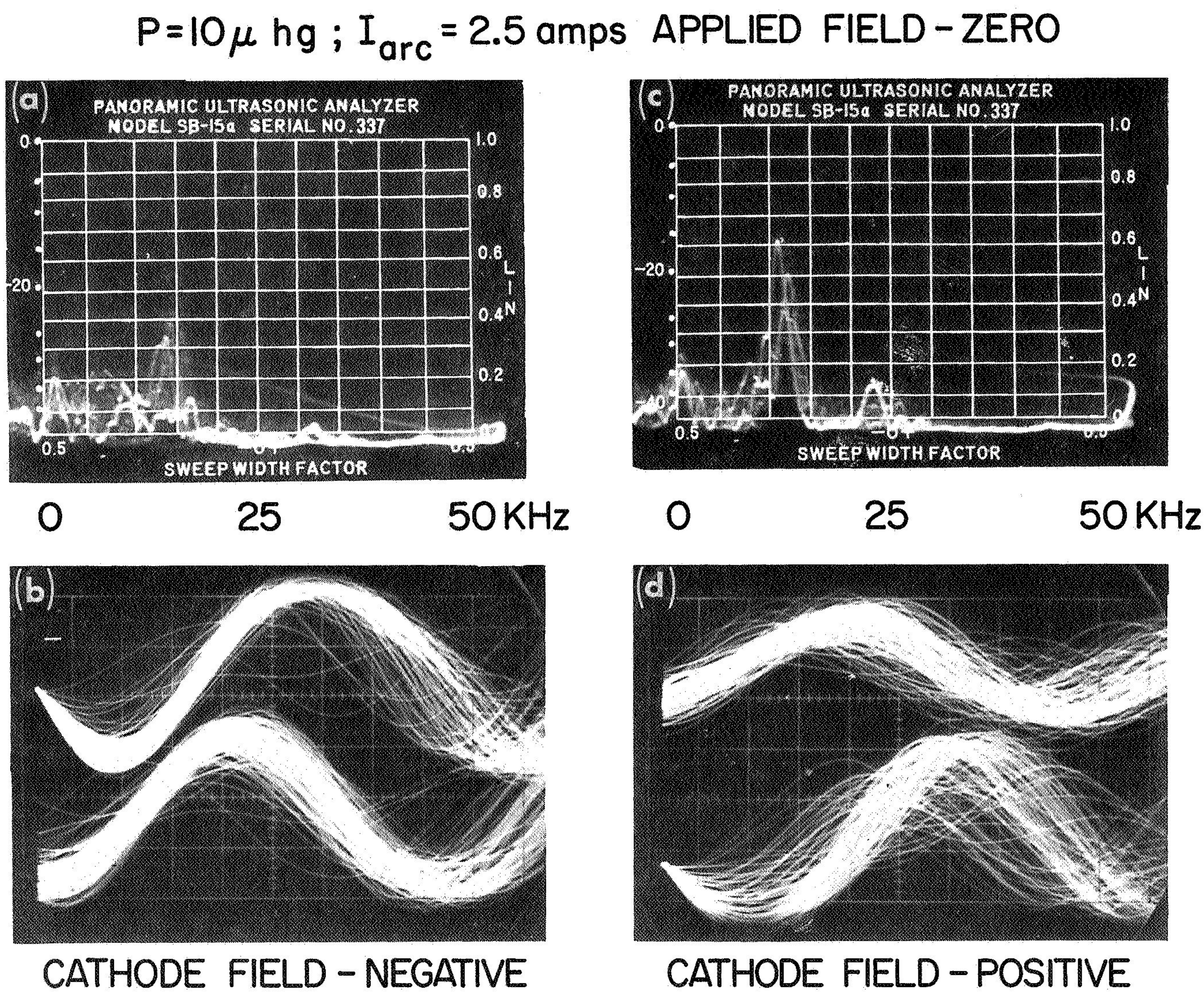

Figure 2.- Frequency spectrum and direction of rotation of voltage oscillations.

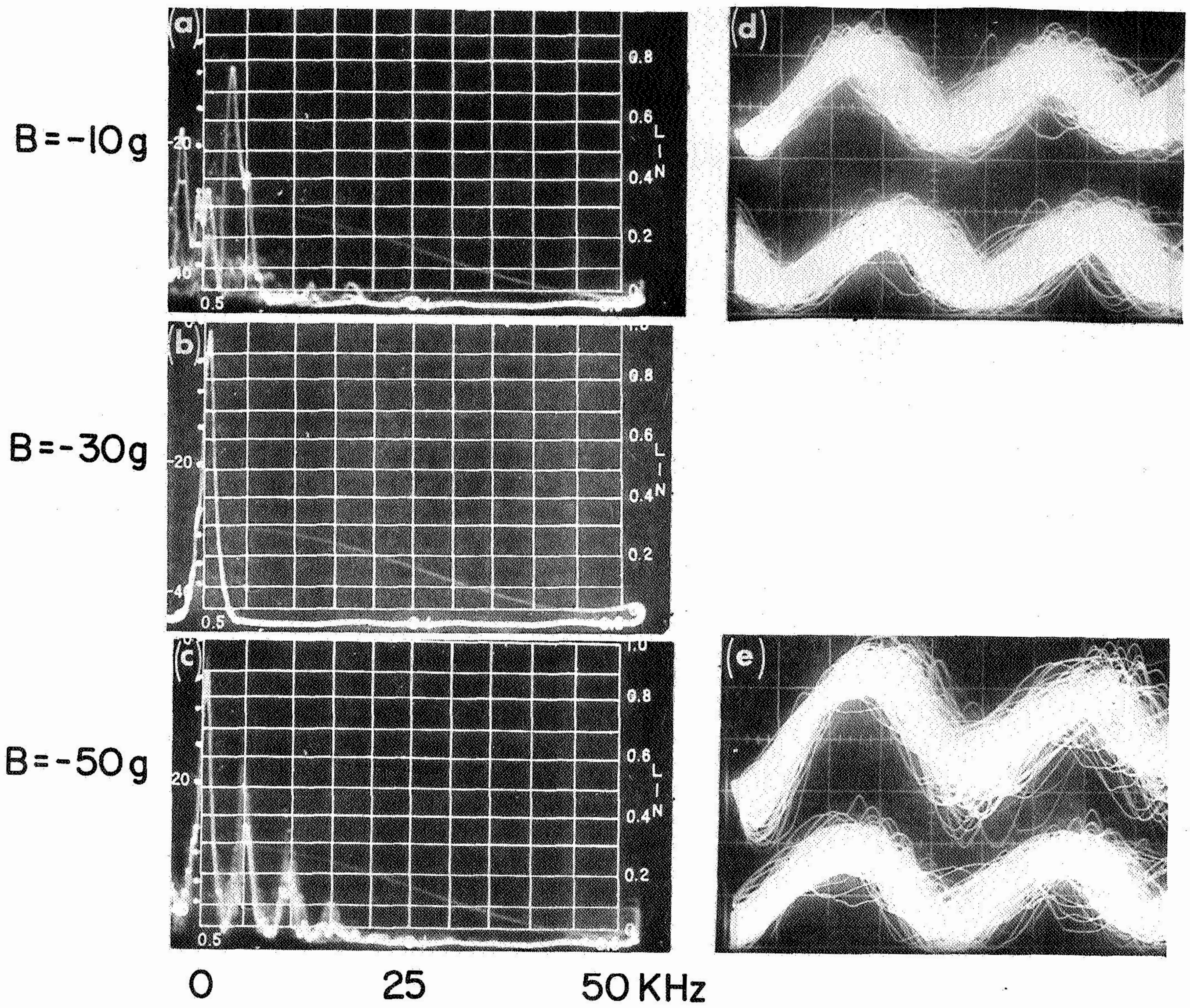

Figure 3.- Frequency spectrum of voltage oscillations.

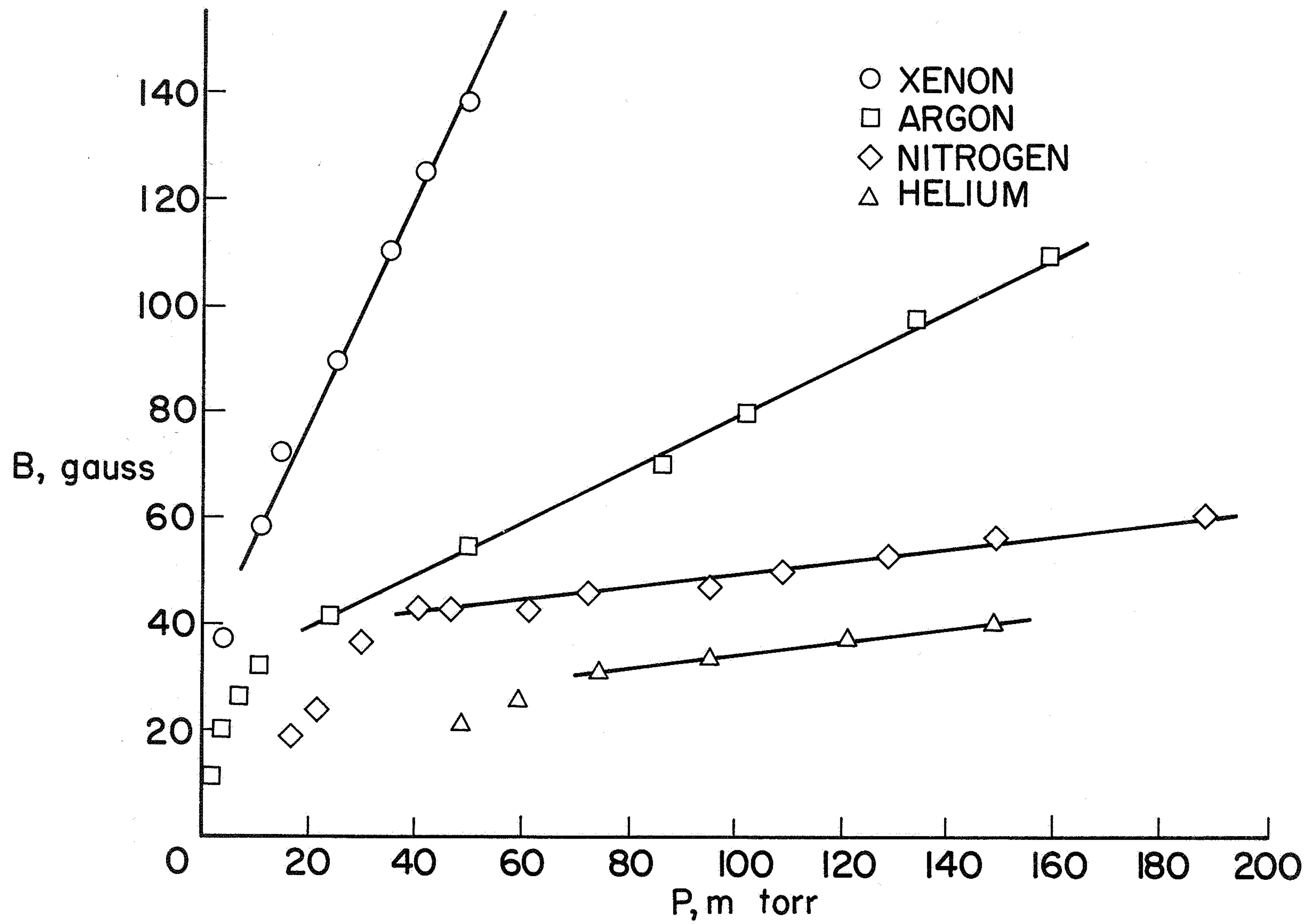

Figure 4.- Critical field versus pressure.

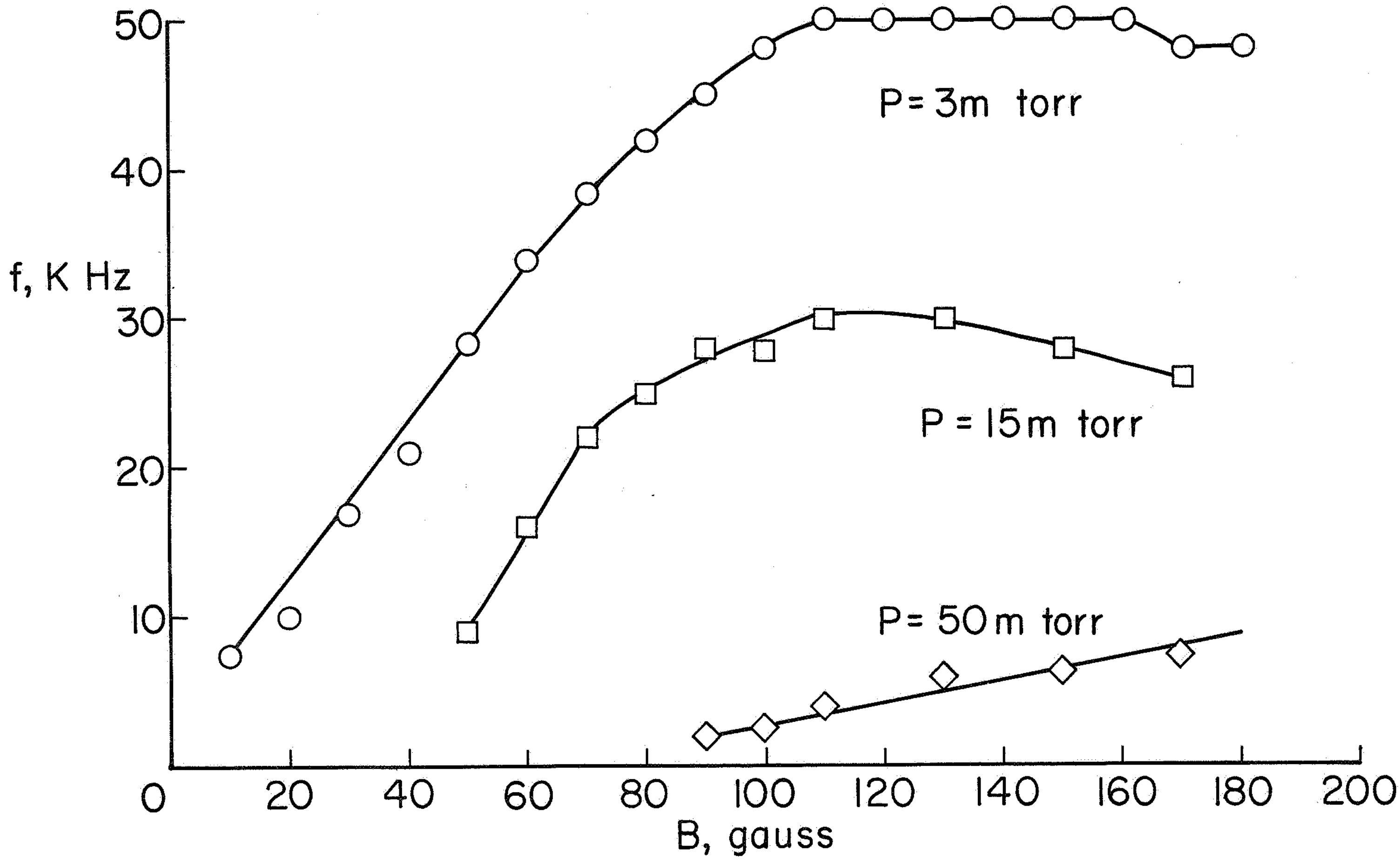

Figure 5.- Frequency versus B in Argon.

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